Removal and Residue Characteristics of Frozen Water Droplets on Cold Aluminum Surface under Ultrasonic Vibration

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Abstract— ***Microscopically visible experiment was conducted, which focus on the removal behavior of frozen droplets at different positions on the circular cold surface under ultrasonic vibration. The experiment summarizes the removal process of frozen droplets, and discusses the residual distribution of frozen droplets in different regions under ultrasonic vibration. According to its shape characteristics, the residual states were divided into three types, Crescent residue, No residue, Intermediate residue. The removed and residual areas were divided into deicing failure zones and deicing effective zones, which were distributed in a circular ring. Thermal effects have a limited effect on deicing. Unevenness of ultrasonic vibration deicing is mainly caused by the uneven surface stress distribution.***

Keywords— ***Ultrasonic vibration ; Deicing ; Residual state ; Thermal effect ; Stress distribution***

I. Introduction

Ice deposition is one of the common phenomena in nature. Icing undoubtedly causes harm in aviation [1,2] , power grids [3,4] , Pv power [5] and other fields. The plane collides with liquids below 0℃ in low-temperature clouds and freezes when flying at high altitudes. The weight of the ice increases the resistance of the aircraft, which easily causes security issues. Icing on transmission lines can cause towers to collapse and wires to break, paralyzing the entire grid and disrupting the power supply. Seriously, 10cm snow layer on photovoltaic panels means that no electricity will be generated regardless of the solar conditions [5] . Therefore, the search for effective deicing methods and their mechanism of action not only has important scientific significance but also has important engineering application value.

Deicing methods are mainly divided into two categories: active deicing and and passive deicing [6] . Passive deicing mainly relies on coating the surface with anti-icing and waterproof materials or injecting lubricating materials into the surface. By reducing the contact time between water and the icing surface, the water is removed before it freezes. Ice adhesion is the main resistance to the ice removal, some superhydrophobic surfaces can have strong icephobic [7-10] by reducing ice adhesion. Common active deicing aspects in engineering include thermal deicing and mechanical deicing. Wang [11] proposed an on-line thermal deicing method with the above downlink catenary as the deicing current loop, and the results showed that deicing effect was favorable during normal operation of the line. Zhu et al. [12] studied the wing electrothermal deicing system using numerical simulation methods, and conducted electrothermal deicing tests in large-scale icing ice wind tunnels, which verified the correctness of the numerical simulation method.

Ultrasound as a widely used technology, with its excellent deicing and defrosting ability gradually into people's vision. Regarding ultrasonic vibration deicing, a large number of literatures have been studied. Jose et al. [13,14] conducted a series of studies on the effects of ultrasound on the ice suppression and deicing effects of helicopter blades. Theoretically, it is pointed out that the horizontal shear wave produced by ultrasonic wave can produce enough interface tension between the ice and the plate to reduce the bonding strength of the ice to the plate and remove the ice. Based on finite element simulation, Shi et al. [15] evaluated and verified the ultrasonic deicing system of different structures, and analyzed the effect of shear stress distribution on deicing efficiency. Daniliuk et al. [16] compared the effects of different piezoelectric materials on the possibility and efficiency of ultrasonic deicing, established a theoretical model applying ultrasonic guided wave propagation theory, and simulated it. Besides, experiments were carried out with aluminum plates and composite plates to verify the feasibility of ultrasonic deicing. Li et al. [17] conducted experimental studies on frozen water droplets attached to cold surfaces under ultrasonic vibration, showing that ultrasonic vibration can instantly remove frozen droplets. Guo et al. [18] used the finite element method to study the ultrasonic deicing method based on aluminum plates, and found that surface stress distribution is uneven.

In conclusion, although there have been a lot of studies on ultrasonic deicing, few studies on the dynamic behavior of ice in the process of ultrasonic deicing, and there is no summary of the location of ice crystal residue after deicing. Therefore, in this study, we analyzed the dynamic behavior of frozen droplets under ultrasonic vibration, and used a high-speed camera to observe in detail the transient process of the removal of frozen droplets from a horizontal circular plate under 20kHz ultrasonic vibration. In addition, according to the uneven distribution of ice crystal residue after ultrasonic vibration, the deicing effective zones and deicing failure zones are divided, and temperature changes in different zones during ultrasonic vibration were analyzed.

II. EXPERIMENTAL METHODS

The schematic diagram of the experimental apparatus used in the test is shown in Fig.1. It mainly consists of four parts, a water droplet freezing system, a high-speed image acquisition system, a data acquisition system and a high-frequency ultrasonic vibration system.

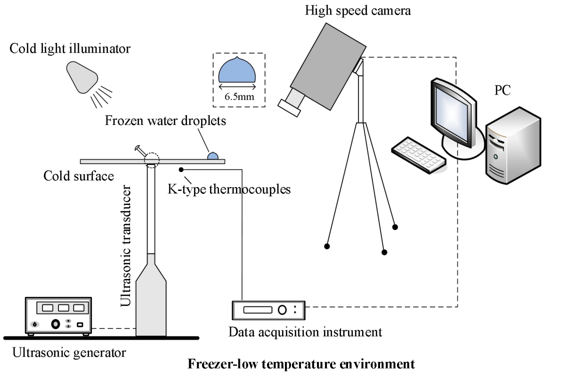
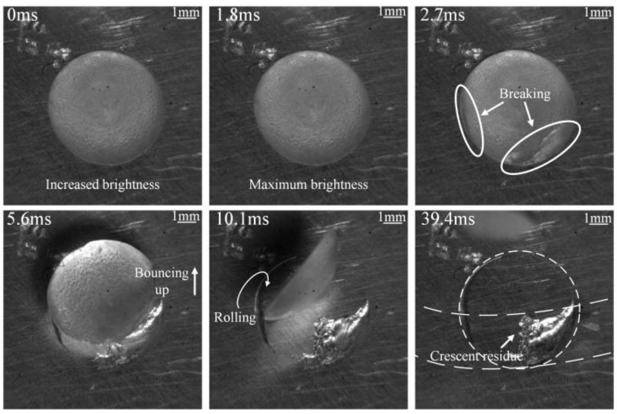
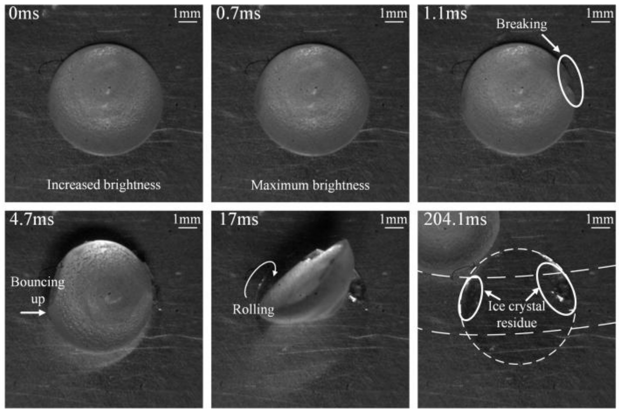


Fig. 1 Schematic diagram of the system for removing frozen droplets by ultrasonic vibration

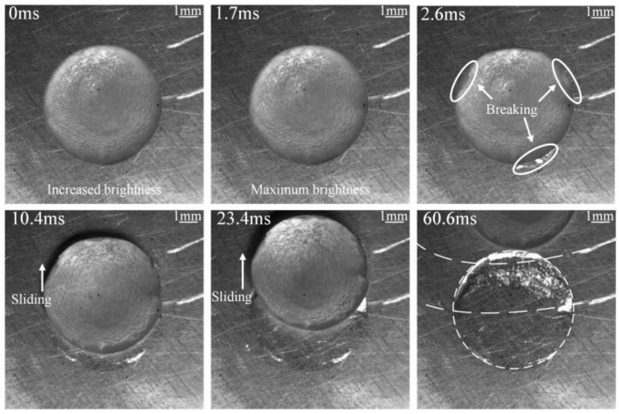
The high-frequency ultrasonic vibration system includes a 20kHz ultrasonic transducer and an ultrasonic generator with a capacity of 0-1800W. As shown in Fig.2, a 6061 circular aluminum plate with a radius of 55mm and a height of 2mm, which serves as the bottom surface for the freezing of water droplets. It is worth noting that Ring-shaped zones can be observed on the surface when the droplets are vibrated in ultrasound, droplet scale in some ring regions is relatively larger. 10 typical locations are selected to place the frozen droplets according to the distribution of zones. Production procedure of frozen droplets is shown in Fig.3. First, place the ultrasonic generator in a commercial refrigerator to keep it level (see inset(a) in Fig.3), a pipette was used to drop the droplets on the surface (see inset(b) in Fig.3) and close the refrigerator door to wait for the droplets to freeze (see inset(c)



(a) Dynamic behavior of point B under ultrasonic vibration



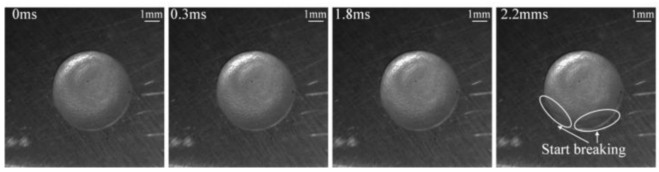
(b) Dynamic behavior of point C under ultrasonic vibration



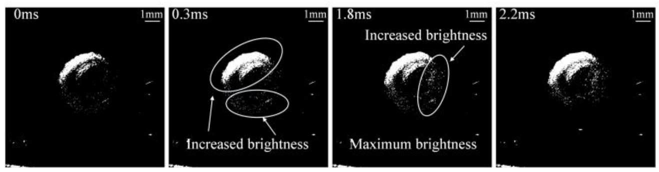
(c) Dynamic behavior of point D under ultrasonic vibration

Fig.4 Dynamic behavior of frozen droplets with diameter of 6.5mm under ultrasound

In order to clearly represent the light ripple transmission process inside the frozen droplets, Fig.5(a) shows the light ripple transmission of 6.5 mm frozen droplet under ultrasonic vibration. Processed image by using image J, as shown in Fig 5(b), 0-1.8 ms is the process of light ripple transmission. At 0.3ms, it can be found that the white spots are more dense in the area where the light ripple is transmitted. At 1.8ms, the right spot of the frozen droplet is more dense, and the brightness of the frozen droplet is the largest. At 2.2ms, the frozen droplets began to break up, the brightness of the broken parts became darker, and the spots in the processed image disappeared.



(a) Light ripple transmission inside frozen droplets



(b) Processing diagram of light ripple transmission process inside frozen droplets

Fig.5 Brightness Changes of Frozen Droplet under Ultrasonic Vibration

The light ripple is generated due to the stress distribution of the surface is uneven when the surface is vibrated by ultrasonic, and the ice located in the area with large stress can overcome the interfacial adhesion force on the surface and cause interfacial separation. However, stress in some areas is not enough to overcome the interfacial adhesion force, the internal structure of the frozen droplet is not destroyed, so the frozen droplet will not be lifted, and the slight interfacial disturbance is the cause of light ripple.

The breaking of frozen droplets is due to the traction generated by the ice layer where the interfacial separation occurs and the stress of the residual area of the ice crystals cannot overcome the interfacial adhesion at the location, and can only destroy the ice layer with less cohesion above the interfacial ice layer, so the location where the frozen droplets break is in an area with relatively small stress, and when the frozen droplets are broken, the frozen droplets will be quickly removed. After the removal of the frozen droplets, the ultrasonic vibration deicing reaches stabilization phase, and continuous application of ultrasonic vibration cannot remove the remaining ice crystals.

A. Deicing zones and residual states of frozen droplets under ultrasonic vibration

According to the residual shapes of frozen droplets, the residue states of frozen droplets under ultrasonic vibration are classified, and deicing effective zones and deicing failure zones are defined, residue states of frozen droplet are divided into three categories, as shown in Fig.6, including crescent residue, intermediate residue, no residue. The residual state of ice crystals are related to the distribution of the deicing effective zones and the deicing failure zones. It can be found that Intermediate residues are placed in the middle of the deicing failure zones, No residues are placed in the center of the deicing effective zones, Crescent residual are at the junction of the deicing effective zones and failure zones.

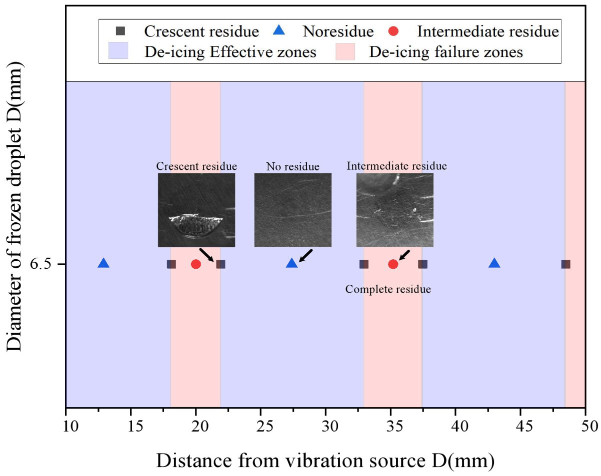
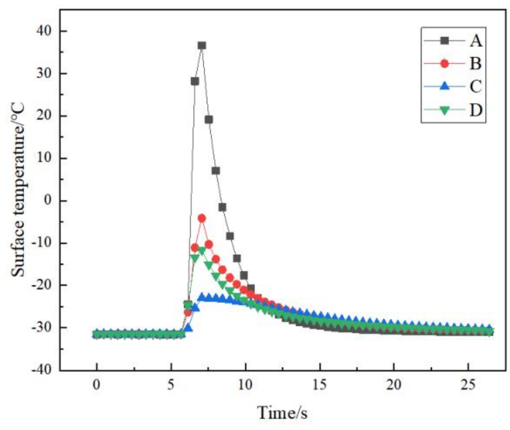


Fig.6 Residual state of frozen droplets under ultrasonic vibration

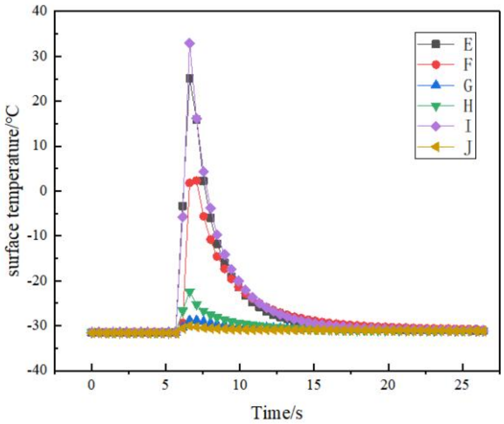
The residual states of ice crystals are mainly affected by the stress magnitude of the deicing effective area and the deicing failure area. Ice in deicing effective zones is separated from the substrate by normal stress and shear stress under ultrasonic vibration, and ice in deicing failure area cannot overcome the interfacial adhesion force driven by a small stress, when cohesion of ice is less than interfacial adhesion, the frozen droplets will break, and the residual state is crescent-shaped due to the circular distribution of the deicing failure zones. When the center of the frozen droplets is placed in the center of deicing failure zones, the other parts of frozen droplets are in deicing effective area, frozen droplet is removed under the joint action of stress on both sides, and ice in the deicing failure area cannot overcome the adhesion force, so that intermediate residues will appear in the middle of the droplet. When the frozen droplet is in deicing effective zones, No residues will appear on the substrate, which is due to the uneven distribution of stress in deicing effective zones , stress in the deicing effective zones is large.

B. Effect of the thermal effect of ultrasonic vibration on deicing.

In order to further explore the effect of the thermal effect of ultrasonic vibration on deicing. Fig.7 shows surface temperature change at the (A-J) position under ultrasonic vibration of 1s. It can be found that under the action of ultrasonic vibration, the surface temperature shows a trend of first rising and then falling, which is due to thermal effects caused by ultrasonic vibration. Thermal effect makes the surface temperature rise. When ultrasonic vibration stops, and temperature gradually decreases and stabilizes to the pre-vibration temperature. Temperature of point A located in the deicing effective zone of the surface can be significantly increased from -31.5 °C to 36.6 °C, points B and D are at the junction of the deicing effective area and the deicing failure zone, point C is in the deicing failure zone, under ultrasonic vibration, the temperature change of point C is small, the maximum temperature is only -22.9 °C, and the temperature of point B and D near the center of the deicing failure zone is -4.1 °C and -11 °C respectively. The same phenomenon was observed in other deicing failure zones and deicing effective zones on the surface. Point E and I are in the second and third deicing effective zones, under the action of ultrasound, the temperature changes significantly, while Point G in the center of the second deicing failure zone, and the maximum temperature is only -28.8 °C under the stimulation of thermal effects. Although the surface temperature changes during the ultrasonic vibration, the ultrasonic vibration deicing is a transient process, during which the thermal effect on the deicing effect is equivalently limited, the temperature rise in the effective area of deicing is mainly due to the stronger stress in the area and the friction with the thermocouple more intense.



(a) Surface temperature at point A-D



(b) Surface temperature at point E-J

Fig.7 Surface temperature variation of temperature measuring points under ultrasonic vibration

III. Conclusions

By visualizing the frozen droplets on the ultrasonically vibrated cold surface, the transient behavior of the frozen droplet removal was observed, and the deicing zones was defined according to the ice crystal residue conditions. The conclusions can be summarized as:

1) The dynamic behavior of frozen droplets is mainly divided into four phases: light ripple transmission phase, separation phase, motion phase, and stabilization phase.

2) After image analysis, it was observed that the frozen droplets of 6.5mm on the cold surface had three ice crystal residual states under ultrasonic vibration, Crescent residue, No residue and Intermediate residue. The residual states are independent of the distance between the frozen droplet and the center of the circular plate, and is related to the stress distribution on the plate.

3) Under the transient ultrasonic vibration, thermal effects have a limited effect on deicing. Unevenness of ultrasonic vibration deicing is mainly caused by the uneven surface stress distribution.

Acknowledgment

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